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The grandstand roof of the Zarzuela Hippodrome in Madrid: The constructive talent of Eduardo Torroja

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INTRODUCTION: THE CONSTRUCTION OF THE NEW RACE TRACK OF MADRID

The old royal race track of Madrid, located in the north end of the Paseo de la Castellana, was demolished in 1933. To build a new one, the Gabinete Técnico de Accesos y Extrarradio de Madrid summoned, on July 6 1934, a design competition. The new construction would be located in the mount of «El Pardo», property of Patrimonio de la República, where they were being carried out the tracks of careers. The proposals should be adjusted to this layout.¹ Nine projects of architects or engineer/architect teams were presented, and the verdict of the jury became public December 18 1934.

The magazine *Hormigón y Acero*, edited by the engineers E. García Reyes and E. Torroja, dedicated the number of November 1934 to the design competition, publishing an article of each one of the authors that presented a proposal to the competition, in which they explain their project.

The project for the new race track included several buildings also the stands, like stables and employees' housings, as well as the urbanization of the environment, organizing the parking areas and the circulations. Overall it was an extremely complex program, as illustrated by the width and depth of the jury's verdict. The building of the stands was the most representative construction in each proposal, furthermore being the one that had a more complex program of uses, and in the one that the solution of the

roof of the tier was the most outstanding structural problem.

THE ARNICHES-DOMÍNGUEZ-TORROJA PROPOSAL

The Carlos Arniches, Martín Domínguez and Eduardo Torroja team won with a proposal that does not coincide exactly with the one that was finally built, although the same distribution of buildings and its general aspect remains. The area of spectator stands consisted of three independent aligned buildings: the partners' stand of 30.00 m length, located among those of preferred and general admission (each 60.00 m long). These three blocks and the adjacent restaurant building were united at the level of the track for a continuous gallery, connected through an open arcade (figure 1).

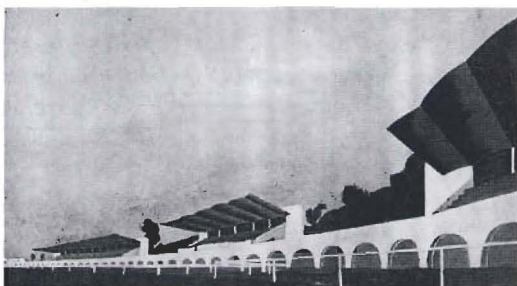


Figure 1
View of the proposal presented to the competition

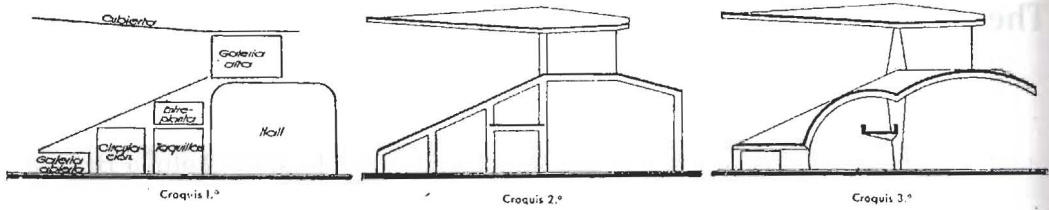


Figure 2
Sketch of the proposal

The grandstand structure is similar in all the proposals: a concrete frame with the roof formed by a cantilever of variable thickness supporting a solid slab. The organization of the transverse section of the buildings arises from the functional program, as the author shows in the outline 1º of Figure 2 below. The design progressed and that it can be materialized according to the outlines 2 and 3 of the figure 2. Comparing them with the proposal, the permanency of the roof type is appreciated, formed by some vaults supported on cantilevers. There is a contradiction between the 3º proposal (as built), in which there is no pier for the hall, and in Figure 3, showing an external pier.

The building consists, therefore, in a sloped stand (A in the figure 3), on which is formed the tier.

Underneath there are two spaces located at different levels, one of them at the level of the tracks B, that is a roofed gallery, and other (C) at a higher level than the tracks and connected with the gallery by a stairway, where the box offices are located. The first space is the «galería de pista» (gallery), and the second the «zona de taquillas» (ticket zone). The roof of the tier continues forming a terrace (D), which roofs the hall (E), contiguous to the «zona de taquillas». This space is called the «sala de apuestas». In the space of «zona de taquillas» there is a gallery in passing (J) placed 2.00 m of the floor, is the «galería de servicio». The tiers and the later terrace are protected by the roof (F) that supports in two elements, the support (G) and the truss (H). This arrangement allows the spectators as much space in

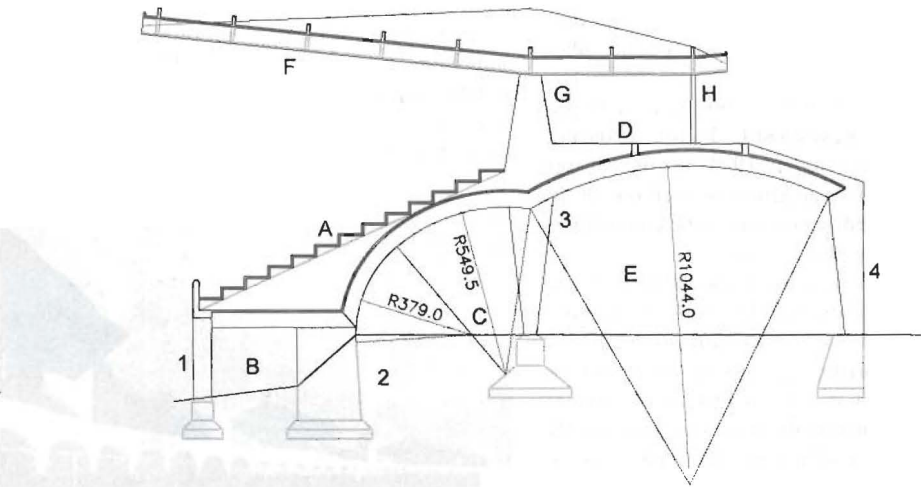


Figure 3
Transverse section of the initial proposal

the tier as in the track, to access the box offices easily. At the same time, a terrace is formed behind the stands from which one can see to both sides.

THE STRUCTURE OF THE GRANDSTAND IN THE PROPOSAL OF THE COMPETITION

The grandstand structure consists of a series of two-story concrete frames, the first floor is supported by four supports, and the roof on two supports. The first floor is formed by a beam of three spans, one horizontal among the supports 4 and 3, and another curved beam between the supports 3 and 2, with a horizontal span until the support 1. In this form the arcade closes the gallery at the track level.

The particularity of these frames, compared to the other proposals, is that the inferior face of the beams of the first plant is not straight, but rather has the form of two circular arch segments, of a larger radius in the area of the hall, and of a smaller radius in the betting area. Among these frames a slab of 6 cm of thickness was placed, reinforced by some ribs of 20 by 10 cm whose inferior face, in the longitudinal sense, has the form of a circumferencial arch. This gives place to a series of span of torus vaults among the frames.

The structure of the roof

The roof consists of a beam of variable edge supported at point G with a cantilever of 12.75 m span, and anchored in a truss (H) located 5.25 m behind the previous one, and another back cantilever of 1.00 m. Among these beams are a series of spans of cylindrical vaults of circular form. The vaults have a 5.00 m span, 55 cm rise and 6 cm of thickness. As stiffener, they are placed, each 2.45 m, some ribs of 20×10 cm section, which are not connected to the support beams (figure 4).

The horizontal thrust of each vault, for a uniform loading, is balanced with those of the contiguous span, giving only a vertical reaction on the cantilever. In the spans at the end of each roof it is necessary to prepare an element with enough rigidity in the horizontal plane to carry the thrust. This situation is solved by making the last half vault become a beam that, working in the horizontal plane, can resist the thrust of the previous section (figure 5). This

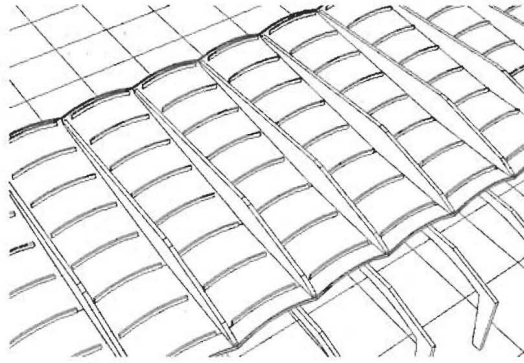


Figure 4
Aerial view of the proposal

horizontal beam is supported in the same supports as the beam of the last frame that, in this case, has to resist the corresponding vertical and horizontal reactions. However, that support has the same section as the others, and it lacks rigidity in the transverse sense. Therefore, to balance the thrust of the roof vaults and the floor vaults (of the same size), some transverse elements are needed to provide enough rigidity. To achieve this, vertical cylinders are placed in the ends of the buildings, whose lateral walls balance the horizontal thrust. We call these structural

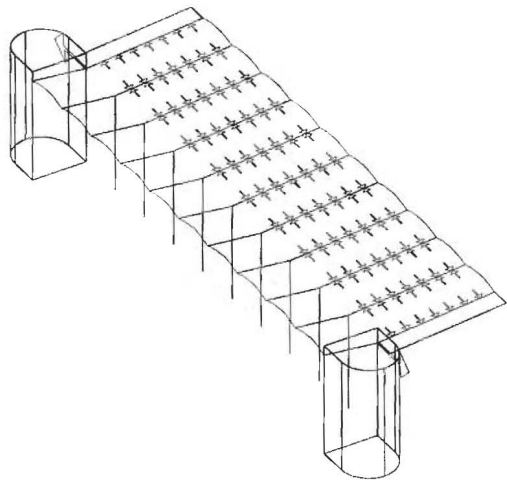


Figure 5
Outline of the horizontal forces in the roof structure

cylinders «*cuerpos de extremidad*». This way, the structure of the roof works as a whole, so that each section is balanced with the adjacent section and the block ends assure the stability of the group.

The disposition of curved elements, in the underside of the beams, and in the transverse section of the roof, distinguished the Torroja structure and the image of the proposal presented to the competition. In the rest of the competition entries, the grandstand roof was straight, while in the Arniches, Domínguez and Torroja proposal, this front was curved, the roof was a series of cylindrical vaults and the roof of the hall was formed by a succession of torus surfaces.

THE INITIAL PROJECT DIFFICULTIES

Between the verdict of the competition, published in December of 1934, and the definitive approval of the project in September of 1935, the authors modified the initial proposal varying, among other things, the roof construction solution. These changes transformed the execution process, eliminating some of the difficulties presented by the initial solution, but without altering the aspect of the buildings. The roof structure consisted of some cylindrical vaults, supported in parallel beams. The formal characteristics of the roof can be summarized as:

- a) from the tier, the roof leaves like a series of parallel vaults;
- b) the beams that support the roof are inclined, rising from the support toward the ends;
- c) the vaults have the same depth in the support as in the end where the roof appears like a succession of arches of 50 cm depth.

These characteristics remain in the final solution, though the radius of the successive transverse sections becomes variable, rather than constant, in the built form. For it, we can think that the structural variations were not made due to formal questions, since the definitive aspect is very similar. The reason for these changes was to simplify the roof construction, by proposing an easier and therefore cheaper construction method.

As stated earlier, the grandstand roof consists of a series of successive spans, mutually balanced, except in the ends, where vault sections work as beams in the

horizontal plane. This way, the whole roof works like a complete structure, of which any intermediate element cannot be eliminated, all are needed to assure the stability. This arrangement led to a construction difficulty, since it was necessary to finish the construction of the whole structure, including the extreme buttresses, for a stable configuration. Therefore, it was necessary to maintain the formwork of the floor and the roof (around 5 000 m²), until all the parts reach the necessary resistance. The result was a higher cost of formwork and scaffolding expense. The position of the ribs of the vault reinforcement, and the beams meant the roof was constructed in three phases, carrying out the slab first, next the reinforcing for the ribs and, lastly, the beams. Again, this resulted in an increase in formwork and construction time. Finally, the roof design, with the ribs and the beams on the exterior of the roof, hindered the water drainage.

In summary, the competition proposal has, at least, three difficulties:

- a) It is necessary to maintain the formwork of the whole roof surface and the floor during the entire construction.
- b) Difficulty of pouring concrete for the ribs and superior beams made it necessary for several successive phases.
- c) A faulty solution to the water drainage.

THE MODIFICATIONS OF THE ROOF STRUCTURE

When facing the necessity of building the tribunes the difficulties of the initial proposal became obvious. Although the process of modification of the project, from the proposal of the competition until the definitive one, is not documented, the date of the project documents allow us to suppose that the new proposal was studied, after the verdict of the competition, between January and May of 1935. During this phase, Torroja carried out a change in the roof structure to solve the inconveniences.

The initial proposal for the competition could be considered like a conventional structure. For it, the ribs of the upper surface of the vault could be cast between the beams. Then the continuous beams would be supported on the cantilevers, and the curved shell built between the beams. Since the distance

between ribs is 2.45 m, it could have been solved with the 6 cm depth proposed. With this alternative the horizontal thrusts would be eliminated, and the necessity of constructing the whole roof once and for all, solving one of the difficulties, although not the other two.

However, from the outset of the competition, the authors show their desire to solve the construction using a shell structure. And, on the other hand, in the months lapsed between the delivery of the project, October of 1934, and the verdict of the competition, December of the same year, Torroja studied several projects of shells structures, some of those were built and they rehearsed several in the months previous to the delivery of the definitive project. In them he checked the possibility to span with concrete shells 5 cm thickness, and without the necessity of using reinforcement ribs in the upper face. On the other hand, the inconvenience caused by the excessive formwork expense in the shell structures was already evident at that time and proposals to solve it, like the marquees of the station of Munich and the garage of Nuremberg.

Torroja's role was decisive in this process, since his office defined the design of the roof. However, it is easy to think that the changes were not immediate, but the result of a series of rough calculations. For

example, one of the drawings of the built project, plan n° 246.229 of the Eduardo Torroja Archive, dated May 1935 (figure 6), defines the geometry and the steel reinforcing of the transverse frame. A section corresponding to the roof element is also drawn whose ends are sections given by a vertical plane. Over that contour there is drawn another profile that cuts the element by an inclined plane. In this way, the crown of the arch at the edge of the shell extends further than the springing line, which is the final form of the shell.

As pointed out previously, one of the causes of the construction difficulties derives from the fact that each roof spans precisely the construction of the other ones to be stable. For that reason, the fundamental change that Torroja introduced was to substitute the vaults supported on beams, for independent cantilevers on each couple of supports, tied together, that can be built independently. Each section becomes a cantilever constituted by two sections of a surface of double curvature whose transverse section has the form of two circumference arches. The radius of these arches varies in each transverse section. The thickness of the resulting element is also variable, from 6 cm at the edge to 75 cm at the support. In the original option, two structures are combined: the cantilever beams and the vaults. In the revised and

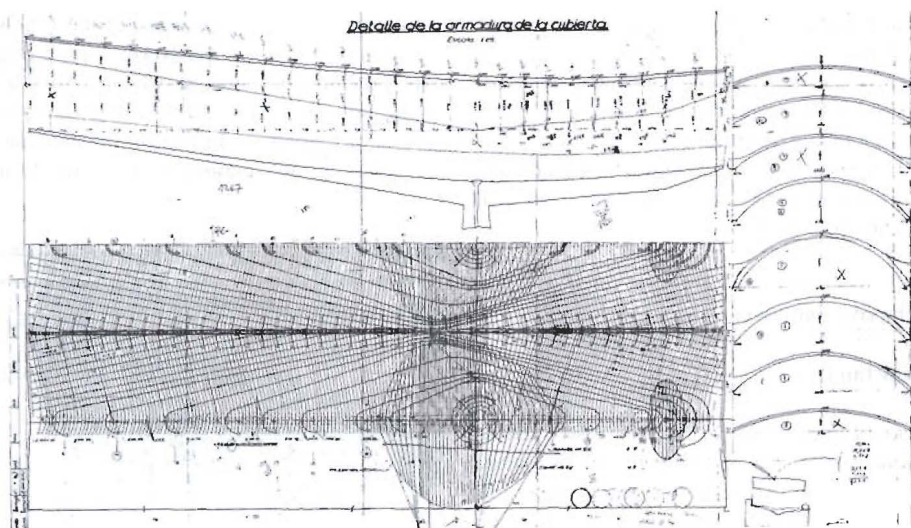


Figure 6
Geometry of the transverse frame

final version, the vaults are the only element, which form the roof and work as a cantilever.

In all the projects presented to the competition, the cantilever had a variable section, with a maximum depth at the support. Therefore, the edge of the roof element at the support will seem like that of the beam that solved the previous structure (in the case of the proposal of Torroja it was 1.50 m deep). On the other hand, one of the conditions of the project consisted on maintaining the form of the front of the roof as a succession of arches 50 cm deep. The roof should be, therefore, a continuous surface 50 cm deep at the border and 150 cm deep at the supports. From there several solutions were possible, such as using a straight line to support each arch, or any other curve type, to form a surface of revolution.

The hyperboloid of revolution is a ruled surface that Torroja had used previously, with the great advantage that straight reinforcing bars can be used which easily correspond to the ruled surface. Also, the surface of revolution can be formed using circular guidelines, whose laying out is easy. With this new structure Torroja solved the previous difficulties, since each element can be built independently of the rest and it is formed by a continuous surface of concrete without projections in their upper face. The concrete pouring can be done much easier as well. This way, the superior part of the roof is a continuous surface for water drainage. It is possible this way to solve the difficulties presented by the initial version.

Torroja modified the project for construction reasons, and the solution he finally adopted shows his ability to approach the problems, making use of the available technology, as a true building engineer. The work of Torroja allowed the proposal to be built, and the initial proposal should be compared to the final solution, and not with the rest of the proposals.

THE DEFINITIVE PROPOSAL

The grandstand

The section of figure 6 shows the transverse frame as it was built, which can be compared to the initial proposal of figure 3. Regarding the one proposed in the competition, the outer supports 1 and 4 of the lower floor were removed and the roof structure was changed. Support 1 could be removed without

problems, because the span is equal to the thickness of the beam at support 2. The support 4 could be removed by taking advantage of the presence of the roof tie whose vertical reaction balances, partly, the weight of the terrace floor.

In the lower floor the same initial solution remained, using a shell structure of double curvature, with the section of a torus, but the stiffening ribs in the upper face of this surface were eliminated. When removing these ribs a new element appears in the section that is not mentioned in the proposal of the competition. It is the beam that unites the central supports in the tribune whose function is to stiffen the frames in the longitudinal sense. When eliminating the upper ribs of the roof, the shell is not, in the authors' opinion, sufficiently rigid to guarantee the stability.

The roof

The new structure of the roof is the most outstanding element in the design. The definition of the module was finished in May 1935 and, to explain it, a longitudinal section was drawn. This defined the dimensions at 28 transverse sections, situated every 75 cm along the cantilever, and at a variable distance around the 60 cm in the rest (figure 7).

The definition of the surface was carried out by thinking of its construction, since each section corresponds with an arch brace of the formwork on which is placed. Each transverse section consists of two circumference arches, which allows a simple laying out. However, the resulting figure is not a surface of revolution. In fact, in the extreme part of the module the sections follow the form of a

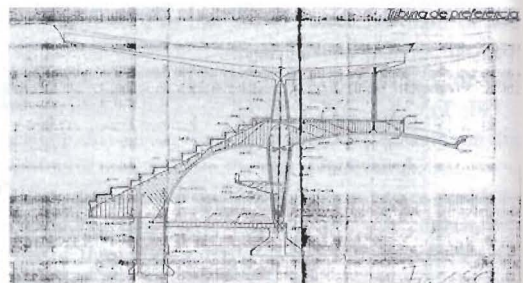


Figure 7
Geometry and reinforcing bars of the roof

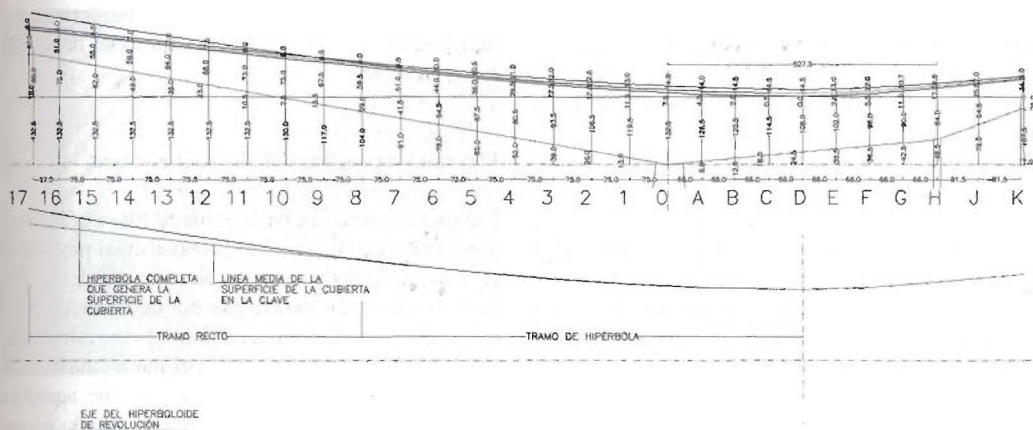


Figure 8
Dimension of transverse section

circumferential arch, but its radius is bigger than that of the corresponding surface of revolution.

With the elevations indicated in the section of the figure 8 each circumferential arch combines to form the lower face of the shell. With the bench marks that define the lower face of the section of the figure, the expression of the equation of a hyperbola has been deduced. This is adjusted quite well to those coordinates, approximately until the section nº 10, starting from which the layout coincides perfectly with a straight line. This way, the curve is defined as a hyperbola and a tangent straight line.

As has already been mentioned, the interior of the roof is not an accurate surface of revolution, because the figure that would be obtained doesn't coincide exactly with the built surface. In figure 9, the surface of revolution starting from the generatrix at the crown (with a horizontal axis) has been superimposed on the form as built. This last would give an elevation of the grandstand so that the roof edge would be a succession of arches of 70 cm depth, more than the arches of the initial proposal.

To obtain the edge for the shell, it was enough to increase the radius of the final arch until the necessary

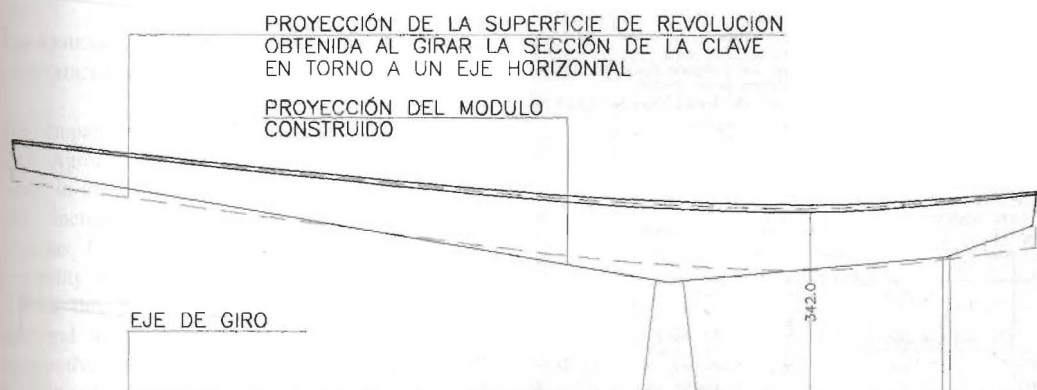


Figure 9
Module built with the surface of revolution superimposed

value so that the depth is achieved. The radius of the transverse sections increases progressively regarding the theoretical corresponding to a surface of revolution with a horizontal axis, from a certain point until the end.

In summary, the modification of the figure of the revolution has three phases:

- to modify the generatrix, substituting the end of the hyperbola for a tangent straight line;
- in the area in the one that the generatrix is a straight line, the radius of the transverse sections is progressively bigger to the one that would correspond to the figure of revolution of horizontal axis, until arriving to the end; and
- the curve that is formed in the intersection of two hyperboloids is substituted by a straight line that wraps this arch (figure 9).

With these alterations of the theoretical surface the definitive form of the roof is obtained that adapts to the geometry of the initial solution and, at the same time, provides a way to generate the surface with the help of circumferential arches, allowing the construction advantages of a surface of revolution. On the other hand, in the area where most of the main reinforcing bars are located, the surface continues

being a hyperboloid, a ruled surface formed by straight lines, where reinforcing bars can be placed without curving.

The reinforcing bars of the roof element

The roof element can be understood like a beam with two cantilevers, in which the fundamental problem is the bending at the support to the main cantilever. The shell structure calculation was not developed in time to make possible an analysis of the structure; however, there were precedents of lineal structures of unrectangular transverse section, like the aqueduct of Tardienta projected by Alfonso Rock whose transverse section resembles a circumferential arch.

In this case, the structure is analyzed like a continuous beam, and the calculation of the sections is made by graphic methods, like those proposed by Zafra. Applying this procedure to several sections of the roof module for the estimates of the self weight, they obtained the depth of the neutral axis and the moment of inertia of the section (figure 10).

The height of the solid part of concrete in the half area of the section is such that the neutral axis is always inside, so that the concrete of the shell is never compressed.

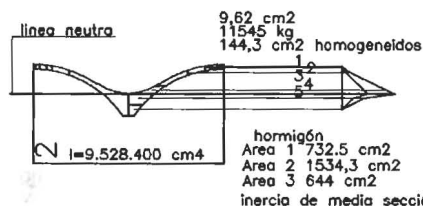
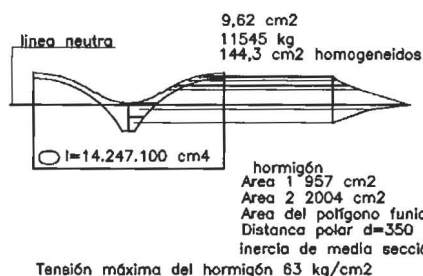


Figure 10
Graphic calculation of the section

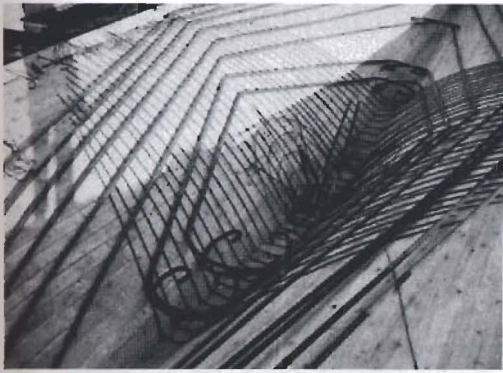


Figure 11
Reinforcing bars in the module

The reinforcing bars organization

To organize the reinforcing bars of the module they used the current methods that consist in adapting the bars to the isostatic stresses. Therefore, the analysis of the structure aimed to obtain the form of these curves. In accordance with this approach, the reinforcing bars were prepared as shown in figure 11.

This form of distributing the bars has a difficult point, in the area where the main bars bend at the line of the supports. At this point, the radial component of the bent bars compresses the concrete of the shell in the transverse sense. To avoid tension at that point they dispensed with the bent bars and increased the thickness of the shell in that edge.

THE REHEARSAL OF THE MODULE AND THE CONSTRUCTION

The company in charge of the construction of the race track, Agroman E. C. S. A., was carrying out several works in the Ciudad Universitaria de Madrid at the time, including the building of the *Facultad de Ciencias*. Its director, Agustín Aguirre, offered the possibility to study a module at full scale.

With this initiative it was gotten, besides the structural load test, the opportunity to study the constructive process, checking the viability of the disposition of the reinforcing bars. In fact, the plans that define the structure are of May 1935, as has been indicated. However, the plan defining the geometry of

the roof and the dimensions and placement of the reinforcing bars, plan 246.228,1, is of June 21, more than one month later. Also, the notation 228,1 was usually used in the Technical Office to designate a plan that substitutes another, which would be the 246.228 in this case. It is probable, then, that they made an initial documentation to carry out the module of the load test and, when making it, adjust the dimensions, including the arch braces and formwork, as well as the length and bent of bars. The final result would be reflected in the plan made later, which is the one that is conserved.

In the rehearsal, the test module was loaded until failure, which occurred with a total load of 605 kg/m^2 . During the course of the loading they registered the efforts taken place in the compressed area and the deformation in the ends of the cantilever that, in the inferior vertex, arrived at 15 cm, and something more in the lateral ends of the edge, since they were not supported with other adjacent sections. It was observed that the transverse deformation in the area next to the support was small. The images of the broken module show two aspects of the behavior of the shell. In the first place, the main work is the bending of the cantilever and the cause of the failure were the radial compression of the main reinforcing bars in the area next to the support where they are bent. (figures 12 and 13) On the other hand, the test illustrated the importance of the deformation of the lateral ends of the shell, regarding the central vertex.

Once the pattern and the load test were carried out, construction began and, in July of 1936, it was



Figure 12
Frontal view of the broken model



Figure 13
The broken model

practically finished. To carry out the formwork of the roof several modules were used successively, so that the necessary scaffolding it occupied only a part of the total longitude of the roof. With that organization, the concrete was poured for modules shown in figure 14, where a completed section appears while the next section is poured, leaving the disposition of the reinforcing bars in the following one and the beginning of the assembly of the last section.

8. DAMAGES DURING THE SPANISH CIVIL WAR. REPAIRS AND INAUGURATION

During the Spanish Civil War, the area was a battle front and the buildings received numerous bombing impacts. This produced several perforations in the roofs, many of which exposed the reinforcing bars. Although none of the roof sections collapsed, the roof



Figure 14
Phases of the roof construction

suffered many fractures, as a consequence of the oscillations caused by the explosive waves of the impacts. The perforations in the sheet were repaired using a formwork with boards of the same dimension as the original, though their localization was difficult. The ends of the cantilever of the final modules only needed to be rebuilt. As it was observed in the load test, these ends had been deformed more than the central vertex of the cantilever, due to the lack of adjacent modules to provide support. This was the situation of the final modules of each grandstand where they did not have an adjacent support, causing excessive deformation. To solve it, these ends were rebuilt again, and reinforced with five diagonal ribs located in the upper face of the shell.

Once the damages were repaired and the ends of the roofs rebuilt, the complete surface was waterproofed, something that had not been carried out before the war. With these modifications, the works of the Zarzuela hippodrome ended in time for the inauguration in May of 1941.

NOTES

1. Antuña Bernardo, Joaquín. 2002. The structures of construction of Eduardo Torroja Miret. Doctoral thesis, ETSAM, Madrid. (advised by Ricardo Aroca Hernández-Ros). This thesis contains the complete bibliographical information.